Gen IV GRNS
October 2-3, 2001
Washington, DC

Report From Gen IV Fuel Cycle Crosscut Group (FCCG)

Reporting Co-Chairs:
David Wade; Charles Forsberg

Status of Report Preparation

- *Due date is Sept. 30, 2001*
- *We are at the 90-95% Completion Status on Editing:*
  - *Will likely be 2 or 3 weeks late in delivery*
  - *Are planning on a subsequent 1 month review period by:*
    - * *RIT*
    - * *TWG's*
    - * *GRNS*
    - * *Professional Colleagues (peer Review of Selected Technical Sections)*

  and if warranted, a final editing tune-up to correct any errors of fact

However,

- *We have Finalized and are in Final Editing of Executive Summary*
  - *FCCG Consensus Principal Findings from our Study*
  - *Fuel Cycle Crosscutting R&D Recommendations*

FCCG Final Report

Table of Contents

Chapter 1: Conceptual Framework; Issues

- ***World Demand Growth Projections for Nuclear Energy***

  Now: 350 GWe

  2050: 2000 GWe World Energy Council/IIASA Case B

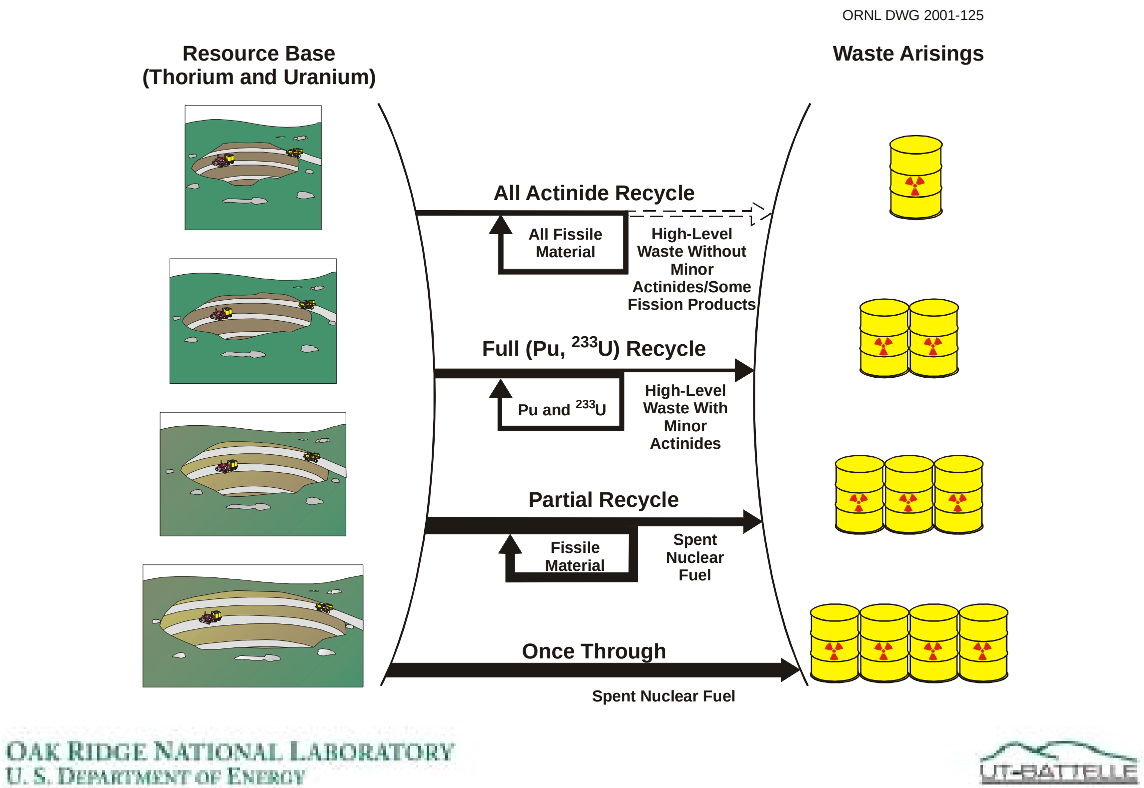
  2100: ~6000 GWe Growth at ~20-25 year doubling time
- ***Projections exclude other applications of nuclear power (hydrogen, heat, etc.)***
- ***World Reserves of Uranium Ore***
  - ***Current Price: 20 $/kgU***
  - ***Projected Resources: ~15 Million tonnes U extractable at < 130 $/kgU***
- ***Current Contribution of Fuel Cycle Services (front and back ends of cycle) <20% of cost of nuclear energy production***

Chapter 2: Gen-4 Concept Types

- *Gen-4 Concept Proposals (>100 concepts)*
  - *Once-Thru, Recycle*
  - *Thermal Spectrum, Fast Spectrum*
  - *U/Pu Cycle, Th/U233 Cycle, Mixed Cycles*
  - *Oxide, Metal Alloy, Nitride, Carbide, Particle, Others*
- *FCCG Organized its Work on Basis of Four Generic Fuel Cycles*
  - *Once-Thru*
  - *Partial Recycle*
  - *Full Pu Recycle*
  - *Full TRU Recycle*
- *Discriminators are*
  - *What is a Fuel*
  - *What is a Waste*

$\}$ → **Relevant to Sustainability Goals**

Four Alternative Fuel Cycles Have Been Defined



Progression of Generic Fuel Cycles: Transforming Wastes to Resources

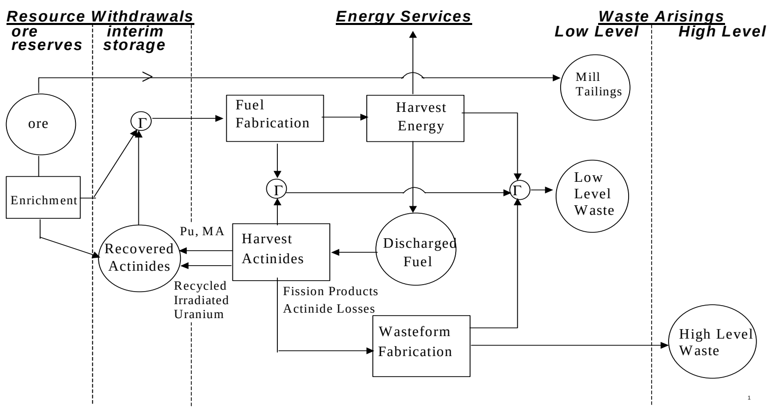


Fig. 1 The Fuel Cycle

	Natural Resources		Fate of Fuel Resource/Waste				Technology Required			
	Virgin Ore	Enrichment Tails	Discharged Fuel				Recycle Technology Used	Remote Refab Used	Thermal Reactors Used	Fast Reactors Used
			Plutonium	MA	Irradiated Uranium	FP				
Once Thru	Fuel	Interim Store	Waste	Waste	Waste	Waste	No	No	Yes	No
Partial Recycle	Fuel	Interim Store	Fuel From UOX	Waste From UOX	Interim Store/From UOX	Waste From UOX	One Pass			
			Waste MOX	Waste MOX	Waste MOX	Waste MOX				
Full Pu Recycle	Fuel	Fuel	Fuel	Waste	Interim Store	Waste	Multiple Recycle			Yes
Full TRU Recycle	Fuel	Fuel	Fuel	Fuel	Fuel	Waste		Yes		

Fig. 2. Designation of Resource and Waste For The Four Generic Fuel Cycles

Chapter 3: Gen-4 Nuclear Energy Scenarios

- ***Year 2000 to Year 2100 Dynamic Scenarios***
- ***Meet demand within physically achievable mass flows***
- ***Scenarios run for Generic Fuel Cycle Type***
  - ***Once Thru; Partial Recycle; Full Pu Recycle; Full TRU Recycle***
- ***Evaluate Performance against Sustainability Goals, SU-1, SU-2***
  - ***Evaluate Ore Drawdowns; Waste Arisings***
  - ***Cost index for Fuel Cycle Services Component (only) of Cost***
- ***Idealized Cases to Serve as Indicators of Physically Achievable Performance Against Gen-4 Sustainability Goals***
  - ***Model Transitions from Current Deployments***
  - ***Model Symbiotic Energy Parks of multiple Gen-4 concepts filling different Market Niches/Functions***
    - ***Mutually beneficial mass exchanges***
- ***Results are Presented Later in the Talk***

Chapter 4: Status of Worldwide Fuel Cycle Technology & R&D

Deployed

- *Water Reactors/UOX Fuel: Dominates Commercial Power Plants*
- *Once-Thru UOX Cycle: Dominates Commercial Fuel Cycles*
- *MOX Mono-Recycle (1/3 core loading) PUREX: commercialized in Europe and is starting in Japan*

Nearly Ready to Deploy

- *Multi (Several) Recycle LWR MOX: PUREX Pu Recycle*
- *Enriched U Coated Particle HTGR Once-Thru*
- *Na-Cooled Fast Reactors with MOX Full Pu Recycle*

Substantial Level of R&D Completed

- *100% MOX Core Loading*
- *Na-Cooled Fast Reactors: U/Pu/Zr Metal Alloy Pyro/Casting Full TRU Recycle*

Chapter 4: Worldwide Fuel Cycle Technology Status & R&D (Cont'd.)

Active R&D

- ***Modified/Advanced PUREX ⇒ Recover MA for recycle***
- ***Pyro and Other Dry Recycle ⇒ Codeposit all TRU***
- ***Simplified/Remote Fab for Radioactive Fuel: Simplified Pellet, Vibro, Casting***
- ***Nitride fuel, Inert Matrix MA or Pu Fuel (for ADS missions)***
- ***Particulate Fuels***
- ***Tailored Waste Forms from Reprocessing: Glass, Ceramic, Metal Alloy***
- ***Interim Storage Technologies***
- ***Repository Site Characterization***

Currently Dormant

- ***Prospecting, Mining/Milling Technologies***
- ***Advanced Enrichment Technologies***
- ***Fuels Designed Specifically to also be Waste Forms***
- ***Integrated Waste Management Approaches: Repository/Interim Storage/Processing as a Coordinated System to manage decay heat and Extend Repository Capacity***
- ***Integrated Intrinsic/Extrinsic Safeguards Regime for Future Fuel Cycles***

Chapter 5: Institutional Issues

- ***A Review for the FCCG was undertaken by OECD-NEA Legal Staff***
- ***Enabling Legal/Institutional Basis and Boundary Conditions for***
  - ***Growing Worldwide Deployment of Nuclear Fuel Cycle***
- ***Issues***
  - ***Safety/Licensing Norms***
  - ***Nonproliferation Norms***
  - ***International Shipping***
  - ***Supplier Liability Treaties***
  - ***Operator Liability Insurance***
  - ***Early Notification Agreements***
  - ***Waste Disposal Laws (Ocean)***
  - ***Radiological Safety Standards***
  - ***Regional Fuel Cycle Service Centers***
  - ***Regional waste Management Services***
  - ***Etc.***

Symbiotic Mixes of Fast & Thermal Systems In A Transitioning Energy Park

- ***The Scenarios are <u>Idealized</u>*** **Water, Gas, Metal** ***Symbioses which Illustrate Physically-Achievable Outcomes***
- ***Insights: Enabling Technologies to Address SU-1, SU-2 Goals in Growing Economy:***
  - ***Flexibility achievable using Multi TRU Recycle/Fast Spectrum Concepts in the mix***
    - ***** Can be a net burner of TRU (waste management: SU-2 Goal)***
    - ***** Can be a net breeder of TRU (resource management: SU-1 Goal)***
    - ***** Can be switched from one to the other with simple change in reload pattern (Short lag time in dynamic response of the power park)***
  - ***Weak impact on cost of sustainability technologies***
- ***Realistic scenarios will be <u>Market Driven</u>***
  - ***Symbiotic Thermal/Fast Power Park Tailored to:***
    - ***** Meet Client Needs & Preferences***
    - ***** Balance TRU production and TRU destruction***
    - ***** Avoid buildup of TRU inventories in storage or repository***
    - ***** Enable a switch to fissile self generation when economics favor it***
  - ***The Degrees of Freedom to Achieve Control of Inventories in the Park***
    - ***** Ratio of Fast to Thermal Systems deployed in the Park***
    - ***** Breeding Ratio of the Fast Systems ($0.5 \leq BR \leq 1.7$)***
    - ***** Timing for making adjustment from burner to breeder (to curtail ore drawdown)***
    - ***** New Finds of ore; higher priced ore; re-enrichment (small economic impact)***

Reference Base Case: LWR-UOX Once-Thru

- ***No Gen-4 Market Penetration***
  - ***LWR-UOX Once-Thru meets Energy Demand to 2100 – with 100% Marketshare***
- ***Outcomes:***
  - ***Redbook Ore Reserves exhausted by 2050***
    - ***New Finds by 2100 = 43 Million tonnes U***
      i.e., about 3 * Redbook Known + Speculative @ <130 $/kgU
  - ***Spent Fuel Arisings Worldwide***
    - ***800,000 tonnes by 2050 I.e., >10 times Legal Limit for Yucca;***
    - ***New repository every 2 years at mid century***
    - ***4,000,000 tonnes by 2100 I.e., ~60 times Yucca Capacity***
  - ***Fuel Cycle Services Cost Index***
    - ***Increase by 15% by 2050***
    - ***Increase by 60% by 2100***

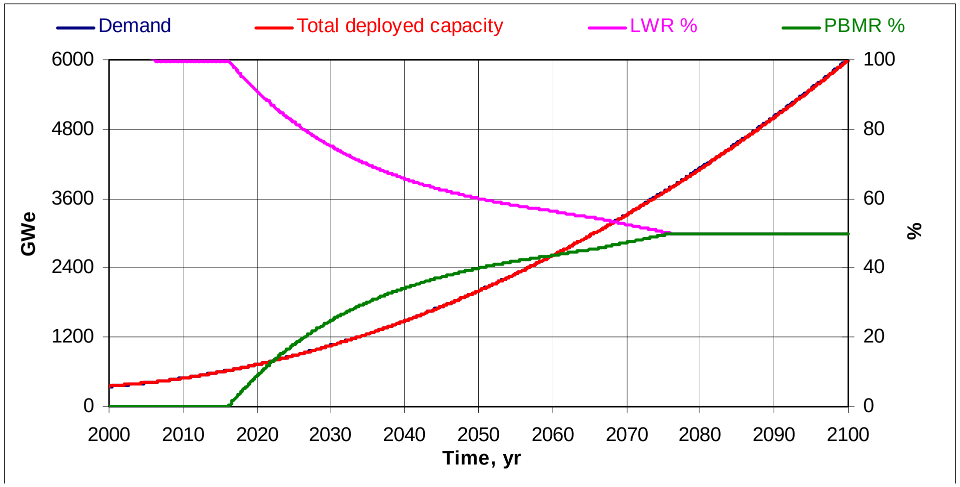
    → **Small impact on cost of energy**
- ***The First Big Issue for Gen-4 Fuel Cycles is Waste Arisings (a problem even before time of Gen-4 Introduction)***
- ***But additionally, Sustainability of Resources (are already a problem by time of Gen-4 introduction)***
    - ***Forward fuel needs of LWR's deployed in 2025-2030 already exceed Redbook reserves***
    - ***<100 year fuel supply is no better than fossil***

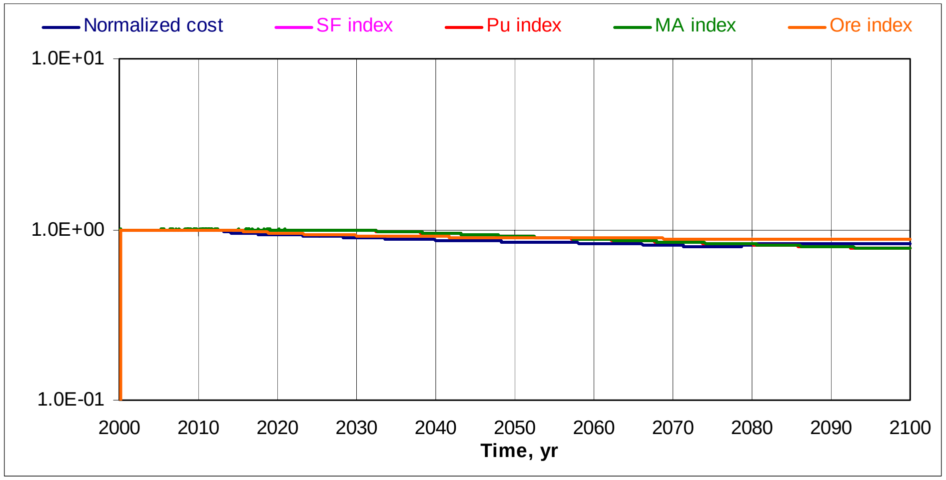
Effects of Higher Burnup Once-Thru: Gas-Reactors

- ***Starting in 2010***
  - ***New Starts: 50/50 market share of PBMR & LWR-UOX***
- ***or***
  - ***New Starts: 50/50 market share of HTGR & LWR-UOX***
- ***Outcomes:***
  - ***70 year transition period to a 50/50 Global Energy Park***
  - ***Currently defined ore reserves exhausted by 2050***

    Higher Enrichment Offsets Higher Burnup and Station Efficiency
  - ***Moderate Reductions in Spent Fuel Waste Arisings***
    - ***Not Much effect by 2050***
    - ***~25% Reduction by 2100***
  - ***Cost of Fuel Cycle Services N/A: (No data available for Gas Reactor Fuel Cycle Services)***

LWR/PBMR 50/50 Deployment: Performance/Base Case

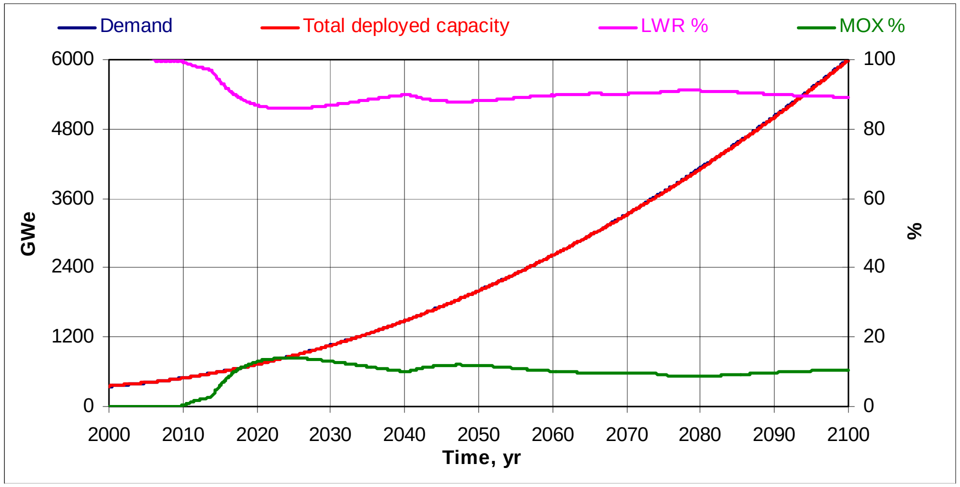


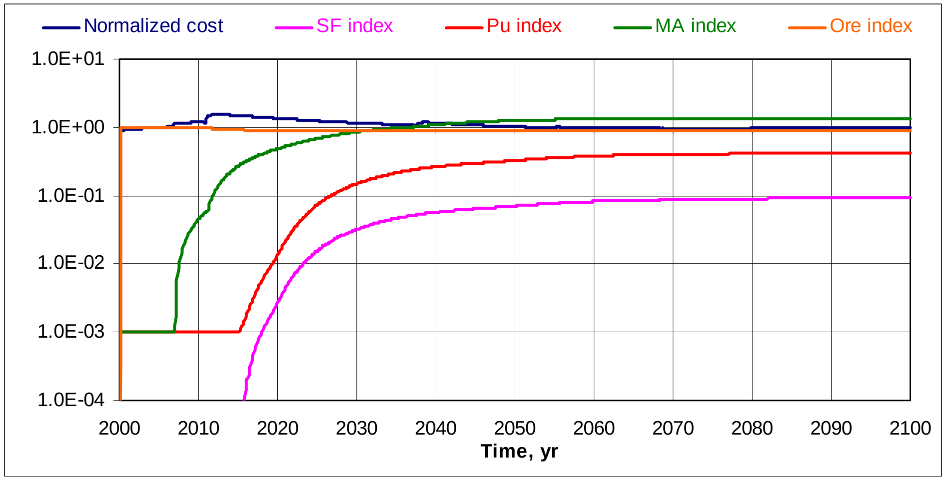


Effects of MOX Mono Recycle

- ***Starting in 2010***
  - ***New starts: 50/50 Market Share of LWR-UOX Once-Thru and LWR-MOX (100% MOX loading) Mono Recycle***
  - ***Pu for LWR-MOX from Reprocessing Existing (and growing) inventories of LWR-UOX Once-Thru discharge***
- ***Outcomes:***
  - ***Symbiotic Mix quickly Settles at 90% LWR-UOX to 10% LWR-MOX Symbiotic Market Share***
    - ***Pu availability from LWR-UOX controls size of MOX fleet***
    - ***20 year transition period***
  - ***Redbook ore Exhaustion Date extended only ~5 years***
  - ***Spent Fuel Waste Arisings Substantially Reduced***
    - * ***Fuel from 90% of park is reprocessed and irradiated uranium (96% of mass) is set aside rather than going to repository***
    - * ***Only Spent MOX from 10% of park goes to Repository***
    - * ***By 2050: ~ 50,000 tonnes of Spent MOX Fuel; by 2100: ~ 360,000 tonnes***
  - ***However, Decay Heat and Toxicity Flow to Repository sees very little reduction***
  - ***Fuel cycle cost Index hardly changes; still dominated by Mining & Enrichment of higher cost ore***

MOX Mono Recycle/UOX Once-Thru Park: Performance Over Base Case

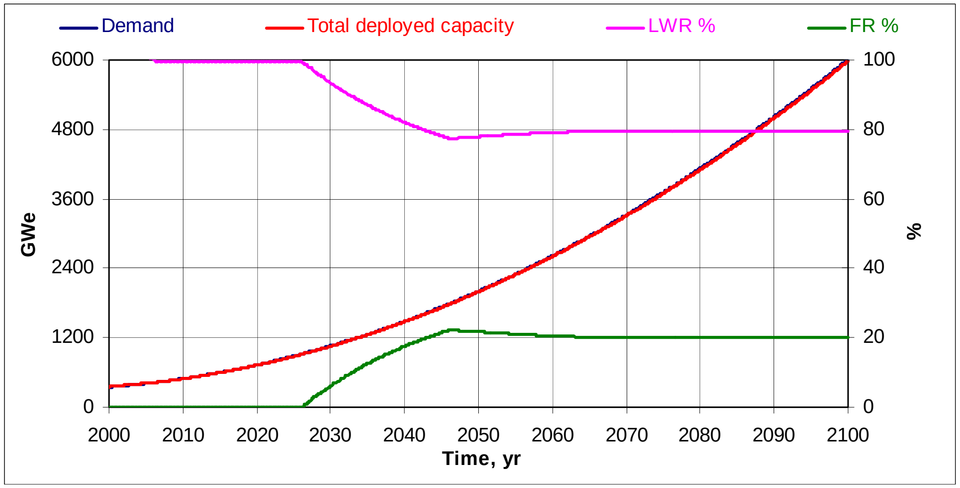


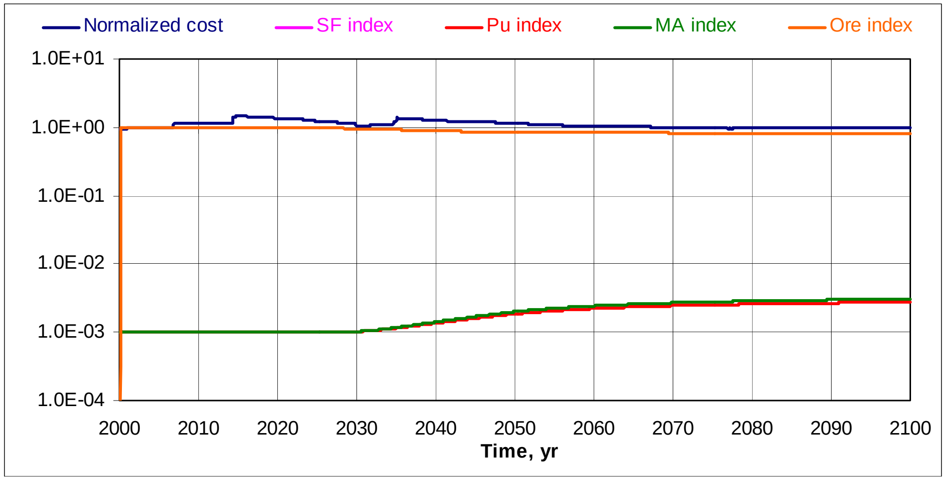


Full Recycle; Reversing The Buildup of Waste In A Growing Economy

- ***Recycle Case I: Thermal/Fast Symbiosis to Reverse the Buildup of Waste***
  - * ***Starting in 2025: New Starts = 63% LWR-UOX Once-Thru + 37% Fast Burners/Full TRU Recycle (breeding Ratio = 0.5)***
  - * ***Reprocess LWR-UOX Spent Fuel Inventories $\rightarrow$ TRU for initial inventories of fast burners***
  - * ***Fuel Makeup of Fast Burners: Self Recycle + discharge from Companion LWR-UOX***
- ***Outcomes:***
  - * ***20 year transition to a 80%/20% LWR & FR Energy Park***
  - * ***Immediate Elimination of all Spent Fuel to Repository***
    - ** ***Fission Products plus trace losses of Heavy Metal is all that goes to Waste Repository (Mass Reductions ~10^3; toxicity ~10^2; decay heat <10)***
    - ** ***Existing and Future inventories of LWR-UOX Spent Fuel worked down to zero***
  - * ***Redbook Known + Speculative Reserves still Exhausted by ~2050 - 2060***
    - ** ***But new finds to 2100 reduced from 43 million to 38 million tonnes of U***
  - * ***Cost index hardy changes***
    - ** ***Still dominated by mining + enrichment (~130 $/kgU ore costs)***
- ***Major Payoff on SU-2; No Significant Effect on SU-1***

Thermal LWR Once-Thru/Fast Burner Symbiosis: Performance/Base Case





Full Recycle; Transition To A Fissile Self Sustaining Energy Park

- ***Can We Meet Energy Demand Within Currently Identified High Assay Low Priced, Ore Resources?***
- ***Approach:***
  - ***Build new capacity with fast breeders within availability of TRU feedstock from Reprocessing LWR spent Fuel (including inventories) and from breeding***
  - ***Make up any deficit in required new capacity with LWR-UOX once-thru***
  - ***Parametrically vary introduction date and Breeding Ratio (doubling time) of the breeder***
- ***Outcomes:***
  - ***Immediately eliminates all heavy metal flows to Repository (Same as Case 1)***
  - ***If doubling time > doubling time of power park***
    - ***Establishes an asymptotic fast/thermal ratio <1 after several decades***
    - ***Extends ore reserves by less than a decade***
  - ***If doubling time < doubling time of power park***
    - ***It's a race between forward fueling requirements for new LWR's exceeding ore resources, vs***
    - ***Displacement of LWR energy fraction in the park by fissile self sufficient breeders***
  - ***Winner depends on three principal things:***

Smooth Transition To Sustainability

- ***Time Window of Opportunity for Successful Transition Depends on:***
  - ***Doubling Time of Demand Growth (slower extends the time window)***
  - ***Doubling Time of Breeders (faster extends the time window)***
  - ***Size of Ore Resource Base (bigger extends the time window)***

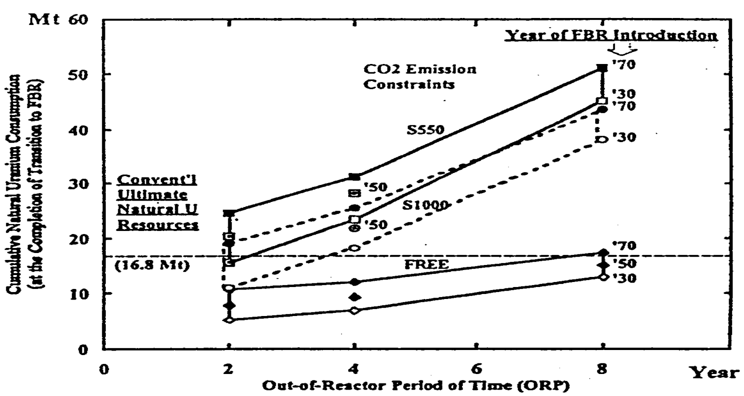


Fig. 24 Map to Search for Optimal Conditons of ORP

Koike et al Global 99

S550 ⓾WEC/IIASA Case B

350 → 2000 → 6000 GWe

S1000 350 → 1600 → 4200 GWe

FREE 350 → 1100 → 2200 GWe

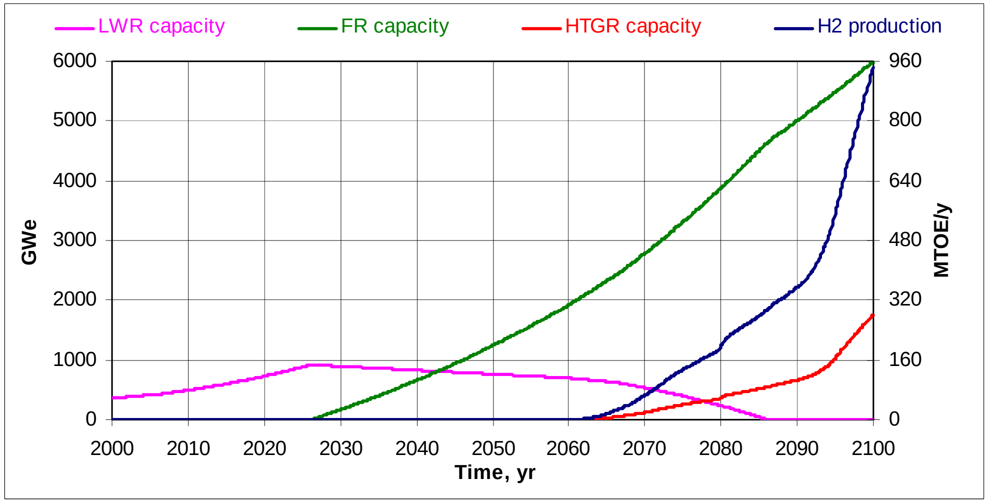
- ***For our assumed demand growth, (WEC/IIASA-B) and Redbook Reserves: date of 2030 is latest to start fast reactor deployment***

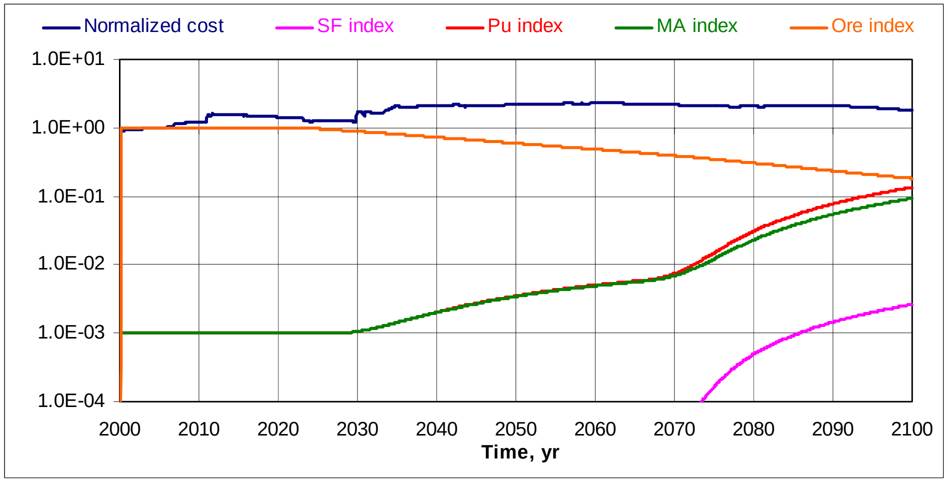
Full Recycle: Expansion of Nuclear Into Non-Electric Energy Service Sectors

Roadmap GENERATION IV nuclear energy systems

- ***Case 3: Evaluate the Limiting Case of Nuclear Market Expansion from Electricity Exclusively Into driving a Sustainable Electricity and Hydrogen Economy***
  - ***Starting in 2025: New Starts = 100% Fast Reactors Super Breeders (BR=1.72) operating on full TRU Recycle***
    - ***Initial Inventories of New Starts: Reprocess LWR-UOX Spent Fuel Inventories***
  - ***Use excess fissile bred in FR's***
    - ***First to refuel breeders***
    - ***Then to support new starts of breeders to meet electrical demand***
    - ***Finally, to support and fuel new starts of the TRU-fueled HTGRs producing H_2***
- ***Outcomes:***
  - ***Immediately eliminates all heavy metal Mass flow to Repository (as before)***
  - ***Transition to fissile self sufficient energy park complete by 2085***
    - ***Within Redbook Known + Speculative Reserves (But waiting until 2035 is too late)***
    - ***Park thereafter fueled by U238 from enrichment tails and irradiated U***
  - ***Penetrates deeply into non-electric energy service sector by 2100***
  - ***Cost index increases by factor of ~4***
- ***Energy Sustainability <u>is</u>*** *Physically* ***Achievable within the 21^{st} Century!***
  - *Practical* ***achievable is unlikely unless demand growth is slowed or more ore is found***

Breeder/HTGR TRU Burner Symbiosis for Electricity & Hydrogen: Performance/Base Case





Waste Attributes: Integrated Waste Management

- ***The Recycle Scenarios***
  - ***Illustrate the transformation of waste to resource***
  - ***In terms of <u>Mass</u> → controls performance against SU-1 Goal***
- ***Specifically***
- ***LWR fuel) is recovered for future use***
  - ***Plutonium (~1% of LWR fuel) is recovered to fuel***
    Initial inventories of new starts
  - ***U (~96% of LWR fuel) is recovered and saved for "fuel"***

But

- ***What about MA and Fission Products?***
  - ***Fission Products (~3 w/o of LWR fuel) dominate for 100 years***
    - ** ***Heat load → <u>controls</u> packing density in Repository***
    - ** ***Radiotoxicity***
  - ***MA (~0.1 w/o of LWR fuel) are major contributor to***
    - ** ***Long-term heat load***
    - ** ***Long-term radiotoxicity → <u>controls</u> the predicted public risk***
- ***MA and Fission Products → <u>control</u> performance against SU-2 Goal***

Needed Developments:

- ***Full TRU (vs Pu) Recycle & Integrated Schemes for Decay Heat Management***

OECD-NEA Study Shows Importance of Minor Actinide Recycle vs Pu Recycle Only

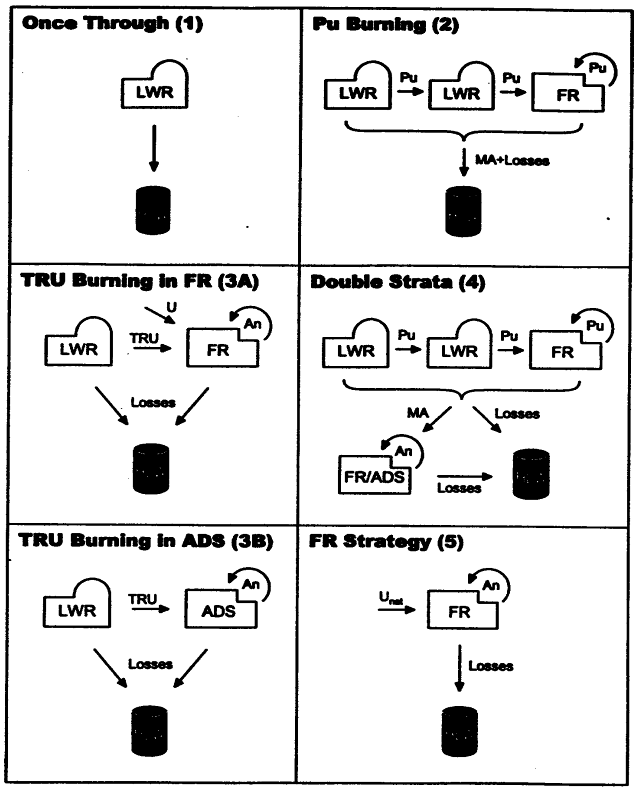


Fig. 1. Nuclear Fuel Cycle Schemes of the OECD-NEA Study

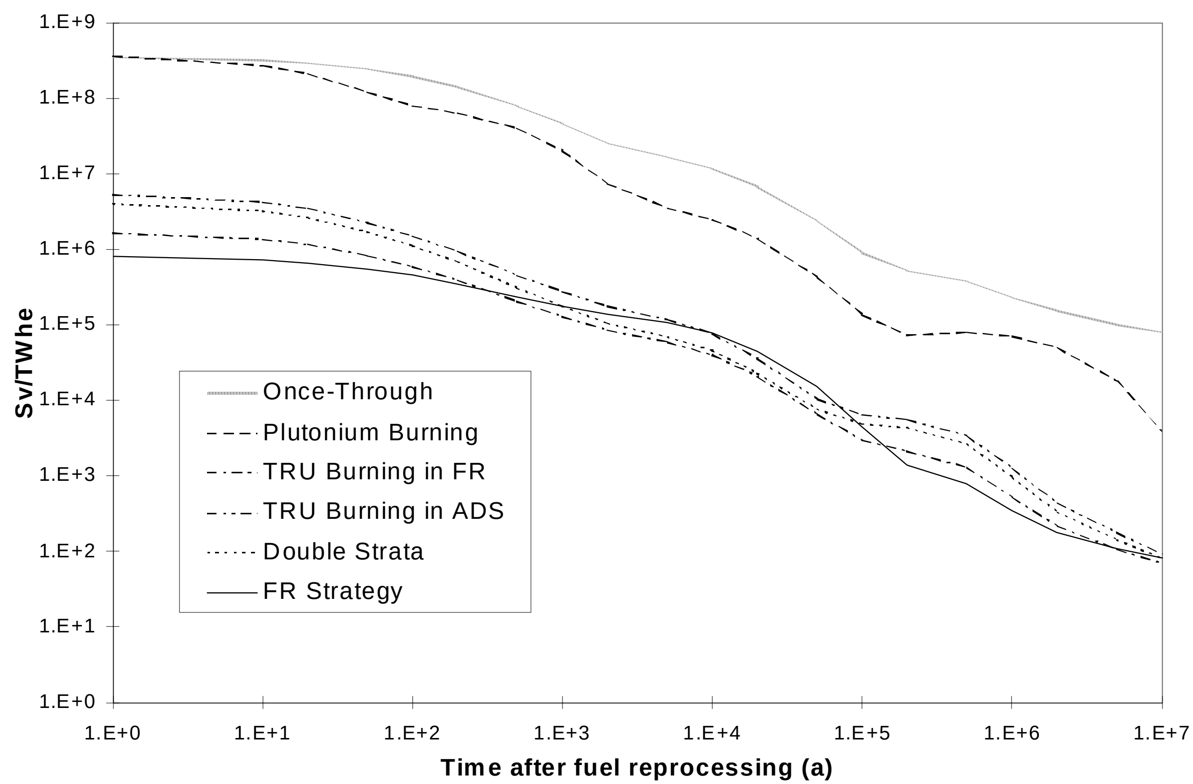


Fig. 2. Evolution of the Actinide Waste Radiotoxicity (Average Burnup of Metal and Nitride Fuel: 150 GWd/t^{HM})

Resource Attributes: Efficient Use of Resources

- ***Uranium resources per se are not the fundamental limitation on the expansion of nuclear power***
- ***Uranium resources are important in two contexts***
  - ***Impacts of uranium mining increase with lower ore grades***
  - ***Increased uranium costs provide incentives to***
    - ***Use more fuel efficient reactors (higher conversion efficiencies***
    - ***Recycle fissile material from SNF***
- ***Waste management costs plus uranium costs place bounds on the allowable cost for new, more fuel efficient technologies***
  - ***Major "conventional" resources at higher costs will surely be found***
  - ***Seawater uranium (~unlimited resource) may eventually be recoverable***
  - ***These place upper bound on cost of alternative cycles***

Chapter 6: Summary, Conclusions, Recommendations

- ***Principal Findings***
  - ***Strong Focus of FCCG Findings on Achieving Gen-4 Sustainability Goals SU-1, SU-2***
    - ***Lessons Learned from Scenarios***
    - ***Lessons Learned from Worldwide Status of Technology***
    - ***Current Worldwide R&D Focus and its Rationale***
  - ***Thermal spectrum concepts dominate the park for 50 years***
  - ***Fast spectrum concepts start penetration no later than ~2030***
    - ***First as waste management symbiosis***
    - ***Later as fuel supply symbiosis***
- ***Recommendations for Fuel Cycle Crosscutting R&D***
  - ***Strong Focus on Technologies which will Produce Payoff on SU-1, SU-2***
  - ***Top Level Recommendations on Areas of Research***
  - ***Detailed Specifics of recommended R&D will Require:***
    - ***Future ongoing interaction with TWG's and new Crosscut Groups***
- ***FCCG Executive Summary Presents:***
  - ***Principal Findings***
  - ***Recommendations for Fuel Cycle Crosscutting R&D Areas***